Neutrino mass constraints on β decay

Takeyasu M. Ito[1] and Gary Prézeau[2]

[1] The Department of Physics and Astronomy, The University of Tennessee, Knoxville, TN 37996
[2] Jet Propulsion Laboratory/California Institute of Technology,
4800 Oak Grove Dr, Pasadena, CA 91109, USA

(Dated: October 19, 2004)

Using the general connection between the upper limit on the neutrino mass and the upper limits on certain types of non-Standard Model interaction that can generate loop corrections to the neutrino mass, we derive constraints on some non-Standard Model $d \to ue^-\bar{\nu}$ interactions. When cast into limits on $n \to pe^-\bar{\nu}$ coupling constants, our results yield constraints on scalar and tensor weak interactions improved by two orders of magnitude over the current experimental limits. When combined with the existing limits, our results yield $|C_S/C_V| \lesssim 5 \times 10^{-3}$, $|C'_S/C_V| \lesssim 5 \times 10^{-3}$, $|C_T/C_A| \lesssim 1.2 \times 10^{-2}$ and $|C'_T/C_A| \lesssim 1.2 \times 10^{-2}$.

PACS numbers: 23.40.Bw,14.60.Pq

arXiv:hep-ph/0410254 v1 18 Oct 2004

Historically, nuclear β decay has played an important role in establishing the $V-A$ structure of the electroweak current of the Standard Model (SM). More recently, precision studies of nuclear and neutron β decay have been used to test the SM and to search for what may lie beyond it. ft-values and various angular correlations, for example, have been measured on various nuclear species to search for small deviations from what the $V-A$ model of weak interactions predicts. These experiments have provided important constraints (for a recent review, see Ref. [1]). With an increased intensity of cold and ultracold neutrons becoming available, increasingly more precise β-decay measurements with free neutrons may probe physics beyond the SM. Neutron β-decay measurements have the special advantage of being less susceptible to uncertainties due nuclear structure corrections. The UCNA experiment [2], currently under construction at the Los Alamos National Laboratory, and the abBa experiment [3], currently under development for the Spallation Neutron Source at the Oak Ridge National Laboratory, both aim at precision neutron β-decay measurements that will provide stringent tests of the SM.

On the other hand, various solar, atmospheric and reactor neutrino experiments have provided clear evidence of neutrino oscillation, hence establishing that not all the neutrinos are massless [4, 5, 6]. In addition, the recent remarkable progress in observational cosmology now allows us to study the "Particle Physics" of the early universe through precision measurements of the anisotropy of the Cosmic Microwave Background (CMB). In fact, the most stringent upper limit on the neutrino mass comes from combining *WMAP* [7] and SDSS [8] data.

The fact that the neutrino masses are so much smaller than the other SM fermions – at least six orders of magnitude – together with the fact that the lepton mixing matrix is strikingly different from the quark mixing matrix, may be a window onto physics beyond the SM. Accordingly, the neutrino mass matrix has become a subject of intensive experimental and theoretical research. At the same time, the search for new physics through low energy observables such as muon decay and β decay continues with increasing accuracy. In view of this situation, model-independent connections between the neutrino mass and other low energy observables would provide valuable guidance in the search for physics beyond the SM.

Recently, an important connection has been pointed out between the neutrino mass and non-SM neutrino-matter interactions in Ref. [9]. That is, if there are non-SM neutrino-matter interactions that involve both right-handed and left-handed neutrinos, they should contribute to the neutrino mass. By evaluating such contributions to the neutrino mass using effective field theory, and requiring that such contributions be smaller than the current neutrino mass limits, the authors of Ref. [9] were able to place non-trivial constraints on various muon decay parameters and the branching ratio of the SM-forbidden $\pi^0 \to \nu\bar{\nu}$.

In this letter, we extend this treatment to β decay. Although we closely follow the notation of Ref. [1], we generalize it to include the possibility of total (and family) lepton-number violation. Therefore, the most general $d \to ue^-\bar{\nu}$ four-fermion interaction involving both left-handed and right-handed neutrino states can be written as

$$H_\beta = H_{V,A} + H_{S,P} + H_T, \tag{1}$$

where

$$H_{V,A} = 4 \sum_{\substack{\epsilon,\mu=\{\mathrm{L,R}\} \\ l=e,\mu,\tau}} a_{\epsilon\mu} \bar{e}\gamma^\lambda P_\epsilon \nu_l^{(c)} \bar{u}\gamma_\lambda P_\mu d + \mathrm{h.c.}, \tag{2}$$

$$H_{S,P} = 4 \sum_{\substack{\epsilon,\mu=\{\mathrm{L,R}\} \\ l=e,\mu,\tau}} A_{\epsilon\mu} \bar{e} P_\epsilon \nu_l^{(c)} \bar{u} P_\mu d + \mathrm{h.c.}, \tag{3}$$

$$H_T = 4 \sum_{\substack{\epsilon=\{\mathrm{L,R}\} \\ l=e,\mu,\tau}} \alpha_{\epsilon\mu} \bar{e} \frac{\sigma^{\alpha\beta}}{\sqrt{2}} P_\epsilon \nu_l^{(c)} \bar{u} \frac{\sigma_{\alpha\beta}}{\sqrt{2}} P_\epsilon d + \mathrm{h.c.} \tag{4}$$

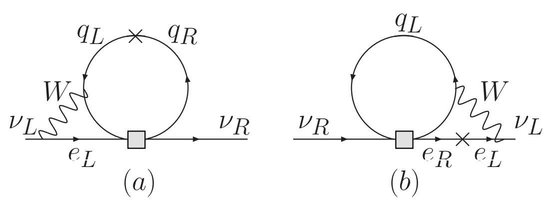

FIG. 1: Two-loop contributions to the neutrino mass generated by chirality-changing non-SM $d \to ue^-\bar{\nu}$ operators. The $\times$ denote mass insertions. Fig. (a) constrains $A_{\rm RR}$, $A_{\rm RL}$, $\alpha_{\rm RR}$ and involves a quark mass insertion $m_q \approx 4$ MeV while Fig. (b) constrains $a_{\rm RL}$ and requires an electron mass insertion, $m_e = 0.511$ MeV.

where, $P_{\rm L,R} = (1 \mp \gamma^5)/2$ is the chirality projection operator, ϵ and μ denote the chiralities of the neutrino and the d quark, respectively, the superscript (c) on the neutrino indicates charge-conjugation for the case where the operators violate total lepton-number violation, while the subscript l takes into account the possibility of family lepton-number violation. In the SM, $a_{\rm LL} = a_{\rm LL}^{SM} \equiv g^2 V_{ud}/8m_W^2$ and all the other coupling constants $a_{\epsilon\mu}$, $A_{\epsilon\mu}$, and $\alpha_{\epsilon\mu}$ are 0. The $d \to ue^-\bar{\nu}$ coupling constants $a_{\epsilon\mu}$, $A_{\epsilon\mu}$ and $\alpha_{\epsilon\mu}$ can be related to more conventionally used $n \to pe^-\bar{\nu}$ coupling constants C_i and C_i', where $i = \{V, A, S, T\}$ [10], as shown in the Appendix. Note that in our notation, the SM corresponds to $C_V' = -C_V$, and $C_A' = -C_A$.

As discussed in Ref. [9], certain types of non-SM interactions generate contributions to neutrino mass through loop effects. In the case of the $d \to ue^-\bar{\nu}$ interaction, the $A_{\rm RR}$-, $A_{\rm RL}$-, and $\alpha_{\rm RR}$-type interactions contribute to the neutrino mass through the diagram shown in Fig. 1a, while the $a_{\rm RL}$-type interaction contributes through the diagram in Fig. 1b [21].

Following Ref. [9], we evaluate the leading log contributions to the neutrino mass from the diagrams in Fig. 1 using dimensional regularization. We do not take into account the factors of $\mathcal{O}(1)$ associated with different types of coupling. The result is

$$\delta m_\nu \approx g^2 N_{\rm c} G_{\rm F} \bar{a} \frac{m_f M_W^2}{(4\pi)^4} \left(\ln \frac{\mu^2}{{M_z}^2} \right)^2 , \tag{5}$$

where N_c is the number of color degrees of freedom, G_F is the Fermi constant $G_F = 1.166 \times 10^{-5}$ GeV^{-2}, m_f is the mass of the fermion for the mass insertion, $g \cong 0.64$ is the SU(2) gauge coupling constant, and μ is the renormalization scale. $\bar{a} = \{\bar{A}_{\rm RR}, \bar{A}_{\rm RL}, \bar{\alpha}_{\rm RR}, \bar{a}_{\rm RL}\}$ is the "normalized" $d \to ue^-\bar{\nu}$ coupling, with $\bar{A}_{\rm RR} = A_{\rm RR}/a_{\rm LL}^{\rm SM}$, etc. Note that $\bar{a}$ in principle can have four indices denoting the flavors of incoming and outgoing leptons and quarks. We suppress the indices here, however, for simplicity.

The value of μ should exceed the mass of the heaviest particle included in the effective field theory – in our case M_W, the W boson mass – while at the same time take into account the scale at which the onset of new physics might be expected. We choose the renormalization scale to be around 1 TeV, a scale often associated with physics beyond the SM in many particle physics models. Since μ appears in a logarithm, our conclusions do not depend strongly on its precise value. A more detailed discussion of the dependence of δm_ν on the renormalization scale is given in Ref. [9] and will not be repeated here.

We use Eq. (5) to constrain $\bar{a} = \{\bar{A}_{\rm RR}, \bar{A}_{\rm RL}, \bar{\alpha}_{\rm RR}, \bar{a}_{\rm RL}\}$ by requiring $\delta m_\nu < m_\nu$ where m_ν is the physical neutrino mass. As in Ref. [9] we adopt the upper limit of 0.7 eV on the sum of the neutrino masses from Ref. [7]. This implies the limit $m_\nu < 0.23$ eV for individual neutrino masses when neutrino oscillation constraints are included.

For Fig. 1 (a), from Eq. (5) with $m_f = m_u$, $m_d \approx 4$ MeV, we obtain $\bar{A}_{\rm RR} < 10^{-3}$, $\bar{A}_{\rm RL} < 10^{-3}$, and $\bar{\alpha}_{\rm RR} < 10^{-3}$. For Fig. 1 (b), with $m_f = m_e$, we obtain $\bar{a}_{\rm RL} < 10^{-2}$. If one takes a neutrino mass limit < 0.04 eV [11] possibly reached by the Planck mission to be launched in 2007 [12], then one obtains $\bar{A}_{\rm RR} < 10^{-4}$, $\bar{A}_{\rm RL} < 10^{-4}$, $\bar{\alpha}_{\rm RR} < 10^{-4}$, and $\bar{a}_{\rm RL} < 10^{-3}$. The obtained constraints on $\bar{a} = \{\bar{A}_{\rm RR}, \bar{A}_{\rm RL}, \bar{\alpha}_{\rm RR}, \bar{a}_{\rm RL}\}$ are summarized in Table. I together with experimental limits, and constraints on quantities derived from $\bar{a} = \{\bar{A}_{\rm RR}, \bar{A}_{\rm RL}, \bar{\alpha}_{\rm RR}, \bar{a}_{\rm RL}\}$, which we discuss below.

Our limit on $\bar{a}_{\rm RL} < 10^{-2}$ is comparable to the present experimental limit from β decay $\bar{a}_{\rm RL} < 3.7 \times 10^{-2}$ [13] (see also Ref. [1]). Our limit is improved by an order of magnitude if the Planck mission constrains the neutrino mass to $m_\nu < 0.04$ eV.

As seen from the equations in the Appendix, $A_{\rm RR}$, $A_{\rm RL}$, and $\alpha_{\rm RL}$ are related to the $n \to pe^-\bar{\nu}$ coupling constants as follows:

$$2g_S(A_{\rm RR} + A_{\rm RL}) = C_S + C_S', \tag{6}$$

and

$$4g_T \alpha_{\rm RR} = C_T + C_T'. \tag{7}$$

Since both g_S and g_T are a quantity of $\mathcal{O}(1)$, our results yield

$$|\tilde{C}_S + \tilde{C}_S'| \lesssim 10^{-3}, \tag{8}$$

and

$$|\tilde{C}_T + \tilde{C}_T'| \lesssim 10^{-3}, \tag{9}$$

where $\tilde{C}_S = C_S/C_V$, $\tilde{C}_S' = C_S'/C_V$, $\tilde{C}_T = C_T/C_A$, and $\tilde{C}_T' = C_T'/C_A$, and we used $C_V \cong g_V a_{\rm LL}^{\rm SM}$ and $C_A \cong g_A a_{\rm LL}^{\rm SM}$.

The current experimental limits on C_S and C_S' come from the e^+-ν correlation in ^{32}Ar β decay [15] and the ft values of super-allowed β decay [16] (An analysis using

TABLE I: Constraints on $d \rightarrow ue^-\bar{\nu}$ coupling constants $\bar{a} = \{\bar{A}_{\rm RR}, \bar{A}_{\rm RL}, \bar{\alpha}_{\rm RR}, \bar{a}_{\rm RL}\}$ obtained from this study (top) and constraints on quantities derived from $\bar{a} = \{\bar{A}_{\rm RR}, \bar{A}_{\rm RL}, \bar{\alpha}_{\rm RR}, \bar{a}_{\rm RL}\}$ (bottom) together with current experimental limits.

$\bar{a}$	Current limits	Limits from this study
$\lvert\bar{A}_{\rm RR} + \bar{A}_{\rm RL}\rvert$	~ 0.1	$\sim 10^{-3}$
$\lvert\bar{\alpha}_{\rm RR}\rvert$	8×10^{-2} (68% c.l.)	$\sim 10^{-3}$
$\lvert\bar{a}_{\rm RL}\rvert$	3.7×10^{-2} (90% c.l.)	$\sim 10^{-2}$

$n \rightarrow pe^-\bar{\nu}$ Coupling	Current limits	Limits from this study
$\lvert\tilde{C}_S + \tilde{C}'_S\rvert$	~ 0.1	$\sim 10^{-3}$
$\lvert\tilde{C}_T + \tilde{C}'_T\rvert$	1.6×10^{-1}	$\sim 10^{-3}$

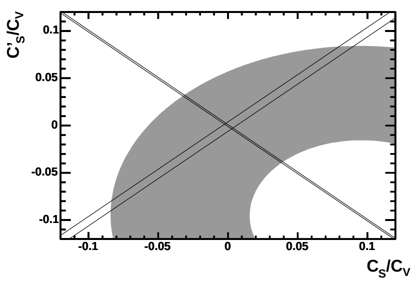

FIG. 2: Constraints on $\tilde{C}_S = C_S/C_V$ and $\tilde{C}'_S = C_S/C_V$. The narrow diagonal band at -45^o is from this work. The annulus gray is a 95% C.L. limit from Ref. [15]. The diagonal band at 45^o is a 90% C.L. limit from Ref. [16].

updated values of the decay rates and nuclear corrections, etc. gives a similar limit [17]). Ref. [15] quotes, as results of a combined analysis of data from Ref [15] and Ref. [16], a one-standard deviation bound of $|\tilde{C}_s|^2 \leq 3.6 \times 10^{-3}$ and $|\tilde{C}'_s|^2 \leq 3.6 \times 10^{-3}$, which implies $|\tilde{C}_S + \tilde{C}'_S| \lesssim 10^{-1}$. Our constraints are more stringent by two orders of magnitude and are compared with the existing limits in Fig. 2 where it is seen that they are complimentary to the existing limits. Combining our results with the existing limits yields $|C_S/C_V| \lesssim 5 \times 10^{-3}$ and $|C'_S/C_V| \lesssim 5 \times 10^{-3}$.

For the tensor interaction, the present experimental limit is provided by ^{6}He β decay [18] and the positron polarization of ^{14}O and ^{10}C β decay [19]. Ref. [18] quotes $(|C_T|^2 + |C'_T|^2)/(|C_A|^2 + |C'_A|^2) < 0.8\%$ (68% C.L.), which implies $|\tilde{C}_T + \tilde{C}'_T| \lesssim 1.6 \times 10^{-1}$. Again, our results provide a constraint improved by two orders of magnitude. Our results are shown in Fig. 3 together with the current experimental limits [22]. When combined with the existing limits, our results yield $|C_T/C_A| \lesssim 1.2 \times 10^{-2}$ and $|C'_T/C_A| \lesssim 1.2 \times 10^{-2}$.

The initial goal of the UCNA experiment is to measure the β asymmetry parameter A using ultracold neutrons at the 0.2% level. With an implementation of additional detectors, the UCNA experiment also aims to measure

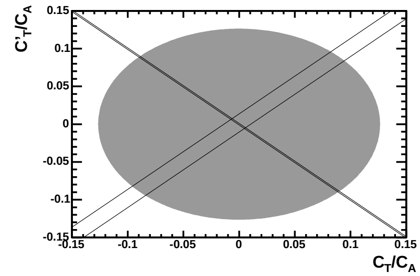

FIG. 3: Constraints on $\tilde{C}_T = C_T/C_A$ and $\tilde{C}'_T = C'_T/C_A$. The narrow diagonal band at -45^o is from this work. The gray circle is a 68% C.L. limit from Ref. [18]. The diagonal band at 45^o is a 90% C.L. limit from Ref. [19].

the $e^- - \bar{\nu}_e$ angular coefficient a, the $\bar{\nu}_e$ asymmetry parameter B, and the Fierz interference coefficient b, with the following accuracies: $\delta_a/a \leq 3 \times 10^{-3}$, $\delta_A/A \leq 10^{-3}$, $\delta_B/B \leq 10^{-3}$, and $\delta_b \leq 2 \times 10^{-3}$. The abBA experiment aims to measure the same quantities with similar accuracies using a pulsed cold neutron beam.

With such precision, it is likely that these free neutron experiments will constrain the scalar interactions by a factor of two better than the current experimental limits [20]. Note that in general β-decay experiments are mostly sensitive to $C_S - C'_S$ and $C_T - C'_T$ through b measurements and $|C_S|^2 + |C'_S|^2$ and $|C_T|^2 + |C'_T|^2$ through a measurements, while our results provide constraints on $C_S + C'_S$ and $C_T + C'_T$, therefore making our method and these experiments complimentary.

The results presented here are quite general and are valid for both Dirac and Majorana neutrinos. As discussed in Ref. [9], there may be cases where the neutrino mass constraints are beaten, for example in the presence of finely tuned cancellations between various Feynman graphs. Also, we do not take into account effects stemming from neutrino mixing with heavy mass eigenstates since in most models they are much heavier than the energy released in β-decay and their emission is kinematically forbidden.

In conclusion, we have calculated the leading contributions to the neutrino mass generated by non-SM $d \rightarrow ue^-\bar{\nu}$ interactions that involve right-handed neutrinos. Using the current upper limits on the neutrino mass obtained from CMB measurements, we derived constraints on the corresponding coupling constants. When cast into the effective $n \rightarrow pe^-\bar{\nu}$ coupling constants, our results improve over the current experimental constraints on the scalar and tensor coupling constants by two orders of magnitude. When combined with the existing limits, our results yield $|C_S/C_V| \lesssim 5 \times 10^{-3}$, $|C'_S/C_V| \lesssim 5 \times 10^{-3}$, $|C_T/C_A| \lesssim 1.2 \times 10^{-2}$ and $|C'_T/C_A| \lesssim 1.2 \times 10^{-2}$.

One of the authors (T. M. I) thanks A. Garcia for valuable discussions.

APPENDIX

Here also, we follow the notation of Ref. [1]. Neglecting the induced from factors, the effective $n \to pe^-\bar{\nu}$ interaction is given by

$$H_\beta^{(N)} \sim H_{V,A}^{(N)} + H_S^{(N)} + H_T^{(N)}, \tag{A.10}$$

where

$$\begin{aligned} H_{V,A}^{(N)} &= \bar{e}\gamma_\lambda(C_V + C'_V\gamma_5)\nu_e\bar{p}\gamma^\lambda n \\ &+ \bar{e}\gamma_\lambda\gamma_5(C_A + C'_A\gamma_5)\nu_e\bar{p}\gamma^\lambda n + \text{h.c.}, \end{aligned} \tag{A.11}$$

$$H_S^{(N)} = \bar{e}(C_S + C'_S\gamma_5)\nu_e\bar{p}n + \text{h.c.}, \tag{A.12}$$

$$H_T^{(N)} = \bar{e}\frac{\sigma^{\lambda\mu}}{\sqrt{2}}(C_T + C'_T\gamma_5)\nu_e\bar{p}\frac{\sigma_{\lambda\mu}}{\sqrt{2}}n + \text{h.c.} \tag{A.13}$$

The $n \to pe^-\bar{\nu}$ coupling constants C_i and C'_i ($i = \{V, A, S, T\}$) are related to the $d \to ue^-\bar{\nu}$ coupling constants $a_{\epsilon\mu}$, $A_{\epsilon\mu}$ and $\alpha_{\epsilon\mu}$ ($\epsilon\mu = \mathrm{R, L}$) as follows:

$$C_V = g_V(a_{\mathrm{LL}} + a_{\mathrm{LR}} + a_{\mathrm{RR}} + a_{\mathrm{RL}}), \tag{A.14}$$

$$C'_V = g_V(-a_{\mathrm{LL}} - a_{\mathrm{LR}} + a_{\mathrm{RR}} + a_{\mathrm{RL}}), \tag{A.15}$$

$$C_A = g_A(a_{\mathrm{LL}} - a_{\mathrm{LR}} + a_{\mathrm{RR}} - a_{\mathrm{RL}}), \tag{A.16}$$

$$C'_A = g_A(-a_{\mathrm{LL}} + a_{\mathrm{LR}} + a_{\mathrm{RR}} - a_{\mathrm{RL}}), \tag{A.17}$$

$$C_S = g_S(A_{\mathrm{LL}} + A_{\mathrm{LR}} + A_{\mathrm{RR}} + A_{\mathrm{RL}}), \tag{A.18}$$

$$C'_S = g_S(-A_{\mathrm{LL}} - A_{\mathrm{LR}} + A_{\mathrm{RR}} + A_{\mathrm{RL}}), \tag{A.19}$$

$$C_T = 2g_T(\alpha_{\mathrm{LL}} + \alpha_{\mathrm{RR}}), \tag{A.20}$$

$$C'_T = 2g_T(-\alpha_{\mathrm{LL}} + \alpha_{\mathrm{RR}}), \tag{A.21}$$

where the constants $g_V = g_V(0)$, $g_A = g_A(0)$, $g_S = g_S(0)$ and $g_T = g_T(0)$ are the $q^2 \to 0$ values of the nucleon form factors defined by

$$< p|\bar{u}\Gamma_i d|n >= g_i(q^2)\bar{p}\Gamma_i n, \tag{A.22}$$

where $i = \{V, A, S, T\}$, and $\Gamma_V = \gamma_\lambda$, $\Gamma_A = \gamma_\lambda\gamma_5$, $\Gamma_S = 1$, and $\Gamma_P = \gamma_5$. CVC predicts $g_V = 1$. $g_A = 1.2695 \pm 0.0029$ [14] (note that our definition of g_A differs from that adopted by Particle Data Group by the sign).

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